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Neuro-behavioral Effects of Luminance Level on Visual Performance and Discomfort with High Dynamic Range Displays

Description

High dynamic range (HDR) displays are designed to simulate the range of perceived brightness afforded by the real world. To study how visual performance and visual comfort are affected by luminance level, 34 participants with normal vision were first asked to discriminate the brightness of two circles presented on LCD and OLED screens to determine the luminance threshold for brightness discrimination. They then judge the orientation of a circular grating target alternating with a luminance circle while their visually-evoked potentials and viewing discomfort was assessed. Results show contrast ratio is more important than luminance difference in brightness discrimination. Regression model based on behavioral outcomes suggest the maximal OLED luminance (647 cd/m^2) was perceived as bright as 1035 cd/m^2 on LCD screen. In discerning grating orientation, the VEP signals associated with the luminance level increased along with viewing discomfort and the signals associated with the grating target decreased along the reduced accuracy of orientation discrimination. The threshold luminance for visual discrimination and discomfort is 695 cd/m^2 . The OLED is visually more comfortable and affords better visual performance than LCD when the screen luminance is high due to its higher contrast and more moderate luminance. These findings suggest higher contrast ratio rather than greater luminance difference is important for brightness discrimination. To reduce visual discomfort while achieving better visual performance in dynamic images, better contrast ratio and black level are more important than greater screen luminance.

Keywords

Luminance threshold, High dynamic range, visual discomfort, visually-evoked potentials

Disciplines

Optometry | Translational Medical Research

Comments

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Technical Report:

**Neuro-behavioral Effects of Luminance Level on Visual Performance and Discomfort
with High Dynamic Range Displays**

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Running Head: Luminance Threshold for HDR Displays

Key words: Luminance threshold, High dynamic range, visual discomfort, visually-evoked potentials.

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Abstract

High dynamic range (HDR) displays are designed to simulate the range of perceived brightness afforded by the real world. To study how visual performance and visual comfort are affected by luminance level, 34 participants with normal vision were first asked to discriminate the brightness of two circles presented on LCD and OLED screens to determine the luminance threshold for brightness discrimination. They then judge the orientation of a circular grating target alternating with a luminance circle while their visually-evoked potentials and viewing discomfort was assessed. Results show contrast ratio is more important than luminance difference in brightness discrimination.

Regression model based on behavioral outcomes suggest the maximal OLED luminance (647 cd/m^2) was perceived as bright as 1035 cd/m^2 on LCD screen. In discerning grating orientation, the VEP signals associated with the luminance level increased along with viewing discomfort and the signals associated with the grating target decreased along the reduced accuracy of orientation discrimination. The threshold luminance for visual discrimination and discomfort is 695 cd/m^2 . The OLED is visually more comfortable and affords better visual performance than LCD when the screen luminance is high due to its higher contrast and more moderate luminance. These findings suggest higher contrast ratio rather than greater luminance difference is important for brightness discrimination. To reduce visual discomfort while achieving better visual performance in dynamic images, better contrast ratio and black level are more important than greater screen luminance.

Introduction

Human vision is achieved through complex neural processes. Of the many factors impacting visual performance and comfort, image luminance has been most extensively studied. In vision, luminance is regarded as the amount of light coming towards the eye from a given area and its subjective perceptual equivalent is “brightness”. As an independent factor, greater luminance increases visual performance until a performance ceiling is reached (Hecht, 1928; Riggs, 1964; Sheedy et al., 2005).

Effect of luminance on visual performance must be considered in the context of surrounding contrast. Contrast is the luminance difference between two adjacent stimuli. Contrast is typically considered as the difference between background and foreground luminance divided by the background luminance. Greater contrast for visual stimuli usually leads to greater perceived brightness and better accuracy in visual recognition (Blackwell, 1971). Greater contrast results in better visual performance and visual comfort until a response ceiling is reached, beyond which higher contrast does not result in better performance whereas visual discomfort can be further elevated (Blackwell and Blackwell, 1946). Recent studies have shown an asymptote at 80% contrast in visual performance for visually demanding tasks (Lin et al., 2006; Yang et al., 2010).

The illuminance of the environment must also be considered when determining display luminance. Imbalance between environment illuminance and display luminance can compromise performance and cause visual discomfort. Previous studies have

established a ratio of 3:1/1:3 for environment illuminance (e.g., reflected luminance from a background wall surface) and display luminance (Sheedy et al., 1984). While identical luminance for background and display is optimal in viewing comfort, any ratio within 1:3 is acceptable and usually does not elicit differential preference for viewers.

The society of Illumination Engineer (1974) recommends specific ranges of indoor illumination for various types of visual tasks. In performing visual search such as inspecting a worksheet, it recommends 500 to 1000 lux, with the higher range for inspecting fine visual details and for older viewers. With this luminance range, the surface luminance reflected from the wall would be between 112 to 224 cd/m^2 , assuming the recommended maximum 70% reflectancy. Based on the 1:3 ratio, the screen luminance should not be lower than 37 or higher than 672 cd/m^2 .

The development of new display technologies poses challenges and opportunities to understand the effect of luminance on visual performance and comfort. Recent creation of high dynamic range (HDR) technology allows the screen luminance to be heightened to a greater level (Mantiuk et al., 2004). HDR is designed to simulate the range of luminance present in the natural world perceivable to human eyes. It does so by distributing the voltage of electric current differently to parts of screen so that a small area can generate extremely high luminance by a greater level of electric current (Mantiuk et al., 2006).

As the heightened luminance in HDR display is designed to simulate the wide range of perceived brightness in human vision, it is critical to understand the actual range of HDR luminance can be appreciate and differentiated by human vision system.

In addition, it is necessary to assess how the elevated luminance level might negatively impact visual performance by overstimulating the visual system and increase visual discomfort in dynamic viewing where luminance changes similar to flickers can occur (Vos, 2003; Vangaite et al., 1997; Shepherd, Kowacs et al., 2001; Kaufman, 1966).

Different display technologies can provide varying luminance ranges for the same HDR images. Presently, the two main types of display panels are liquid crystal display (LCD) and organic light-emitting diode (OLED). LCD screens work by modulating the amount of light passing through from the back to the front of the screen. As such, various levels of light leakage are present and can reduce intended image contrast by permitting too much of background light to pass through the liquid crystal. OLED emits light by passing electric current through organic materials to generate light, with which no backlight is needed and the intended dark background can be achieved. However, the backlight employed by LCD can be modulated by the level of electric current and generate a very high level of luminance at the expense of high electricity (voltage) demand, whereas the OLED light is limited by the emitting capacity of organic materials themselves. Because of the different screen characteristics offered by LCD and OLED, the same level of screen luminance might not be perceived as the same. It is poorly understood how the various level of dark background might affect the perceived brightness of the high-luminance visual stimulus on a HDR display.

The present study aimed to investigate whether a threshold luminance level on HDR displays can be identified beyond which no additional brightness can be differentiated. In addition, the study examined whether visual discomfort can be

induced and visual performance degraded by the higher luminance in the upper range of screen luminance. To these ends, participants were asked to identify the brighter one of paired images displayed on high-luminance LCD and OLED displays. In addition, a homogenous luminance circle and a grating target were alternately presented while participant's visual discrimination accuracy and accompanying visually-evoked cortical potentials (VEPs) were recorded. Subjective discomfort was graded using analog scales after a block of trials with the same luminance circle. Amplitudes of VEP signals were analyzed in relation to discrimination accuracy and viewing discomfort. Finally, viewers watched movies on the two screens and their viewing symptoms before and after 30 mins of viewing were analyzed.

Methods

Participants

Thirty-four participants (18 to 40 years, mean \pm SD = 26.7 \pm 5.6 years) were recruited from the communities around the Forest Grove campus of Pacific University in Oregon. They had normal vision (better than 20/25 binocular acuity, 16% contrast sensitivity and normal color vision), normal pupil and accommodative responses to light, and have no known epileptic responses to light stimulation.

Measurements

Luminance comparison task. To test participant's ability to differentiate luminance levels generated by the LCD and OLED displays, two homogenous circles (5° in diameter) with selected adjacent gray levels (28, 47, 66, 85, 104, 123, 141, 160, 179,

198, 217, 235, 255) were presented simultaneously for 150 ms (Figure 1A). A fixation cross appeared first and the two circles were displayed 500 ms later along the horizontal meridian and their centers 3.725° away from the center of cross. Participants were required to indicate which circle was brighter with left and right keys as soon as possible.

Orientation discrimination task. A circle (9° diameter) with homogenous luminance (gray levels 28, 66, 104, 141, 179, 217, 255) was displayed for 50 ms and then replaced with a circle of the same size with vertical or horizontal gratings for another 50 ms (Figure 1B). The homogenous circle returned for another 50ms. This was repeated until a key response was given to indicate the orientation of the grating (left key = Horizontal; down key = vertical) or when a 2000 ms deadline was reached. An inter-trial interval of 1000 ms was enforced. There were 20 consecutive trials with the same luminance level for the homogenous circle in a block; its luminance was changed to a different level for the next block of 20 trials. The luminance was randomly assigned in each block. The grating target had the same gray levels for the brighter (65) and darker (44) lines, which was kept constant across all blocks; the only change was the orientation of grating lines. Duration of the test was around 30 mins.

Additionally, the same type of orientation discrimination trials was conducted with chromatic luminance circles and grating targets with matching colors (e.g., blue circle and blue/yellow grating target). Four types of chromatic trials were conducted (blue vs. blue/yellow, yellow vs. yellow/blue, red vs. red/green, green vs. green/red). The circle's luminance was set at four gray levels (87, 143, 199, 255) and varied from

block to block. The grating stimuli were composed of brighter (gray level 199) and darker chromatic lines (gray level 87).

Viewing discomfort. Perceived discomfort during each block of trials with the same level of homogenous luminance circle. Participants viewed an analog scale shown on the TV and used the mouse pointer to indicate the level of discomfort.

Movie viewing symptoms. A 15-question questionnaire was used to measure symptom levels before and after movie viewing. Participants used an analog scale displayed on the screen to indicate their perceived level of symptoms (see Table 1). These were measured before and after movie viewing on both TVs. The average score of these 15 questions was calculated to determine the symptom level.

VEP recording: Amplitude and latency of peak neural activity in the primary visual cortex in response to the processing of homogenous luminance circle and grating targets were measured by averaging over the 20 trials of the same luminance level in a block.

Apparatus

Display devices. Two 65" TVs (Samsung 65" QD UHD curved TV and LG 65" OLED UHD TV) were utilized to display the test images in two separate sessions. Both TV utilized the High Dynamic Range (HDR) technology to increase the screen luminance. Figure 1C shows the luminance measured from these two TVs with HDR turned on.

VEP recording system. A 32-channel BrainVision acti-CHamp recording system with 8 auxiliary channels was used to record the VEP signals from the Oz electrode position (Fz position and forehead as reference and grounding sites respectively).

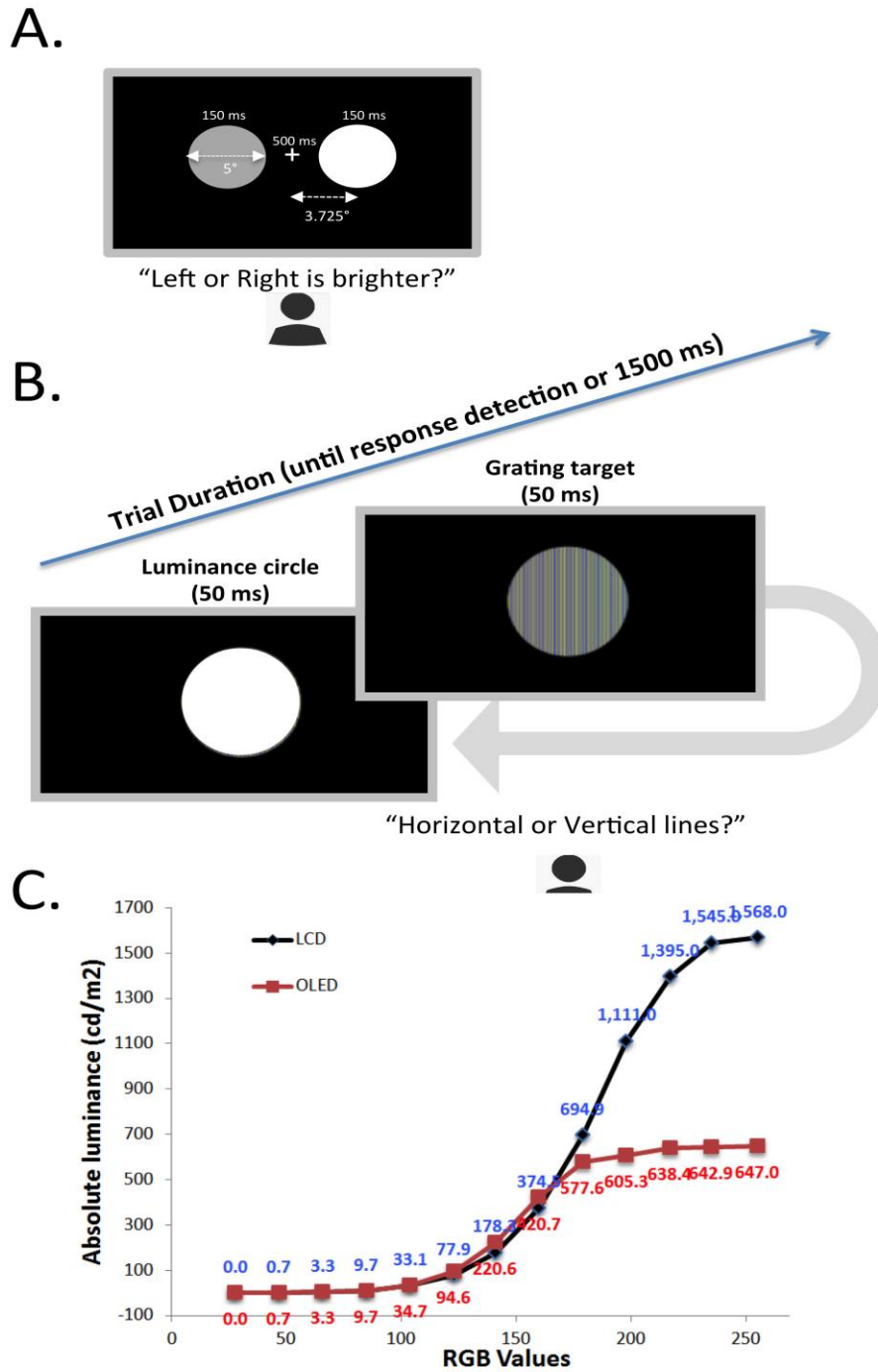


Figure 1. Study design and luminance of HDR images. A) Spatial diagram of luminance comparison task. B) Temporal sequence of orientation discrimination task. C) Absolute luminance measured from images with specified gray levels displayed on the LCD and OLED TVs under the HDR mode.

Experimental procedures. Informed consent, surveys and visual exams were conducted to qualify the participants. They were then seated in front of the screen with his eyesight aligned perpendicularly to the center of the screen. The height of the screen was also adjusted to provide a perpendicular viewing angle. EEG electrodes were placed on the participant and their impedance level calibrated. Each participant attended two sessions of testing, with a different TV in each session. The tasks were conducted based on the sequence described above. Breaks were allowed between blocks of trials. Additionally, the participants viewed a movie with dynamic scenes and high luminance (“The Everest”, Universal, 2015) for 30 mins and visual symptoms were measured before and after viewing. The total testing lasted about 2 hours.

Data analysis. VEP signals were filtered (band filter between .5 and 50 Hz) and segmented into 350 ms epochs (100 before to 250 ms after grating target onset). VEP signals from the 20 trials in the same block were then folded to provide average curves for each condition. A 20 to 90 ms window was chosen to identify the N1 component associated with the homogenous luminance circle and a 70 – 140 ms time window for the N1 component associated with the grating target. The peak amplitude and latency of the N1 components were then taken to assess the visual discrimination process for these two stimuli. Generalized Linear Models were conducted to determine effect of screen luminance level on response accuracy and VEP amplitude. Subjective discomfort was analyzed in relation to these luminance levels using Z tests and non-parametric procedures.

ROC curve analysis was conducted where the actual luminance difference and the contrast ratio of the two stimuli was the test stimuli and the correct choice of the brighter target was the desired outcomes. The ROC curve is the relationship between false alarm (1 - specificity) and correct selection (sensitivity). When there was no difference in perceived brightness, the likelihood of false alarm will be the same as correct hit. When the brightness discrimination was perceptually certain, the false alarm rate should be always zero and correct hit 100. Such a relationship can be quantified as the proportion of Area Under Curve (AUC), with random guessing resulting in a ROC curve along the diagonal line and complete certain resulting in the total area under the curve. A larger AUC value indicates a better test stimulus for discrimination.

Finally, to quantify the effect of contrast ratio on visual discrimination, regression models were evaluated to assess their R^2 and contrast threshold. This was accomplished by calculating the response accuracy of luminance comparison and the contrast ratios for each pair of targets. Contrast ratios higher than 1 usually led to a very high accuracy (close to the ceiling of 100% correct) and can distort the regression model. Therefore, contrast ratios higher than 1 was excluded from the regression analysis. Based on their regression outcome, a threshold of 75% accuracy was then used to obtain the threshold contrast ratio. This threshold contrast ratio was then used to estimate the range of equivalent luminance, i.e., how much higher a luminance level should be in order to produce a reliably difference in brightness perception.

Results

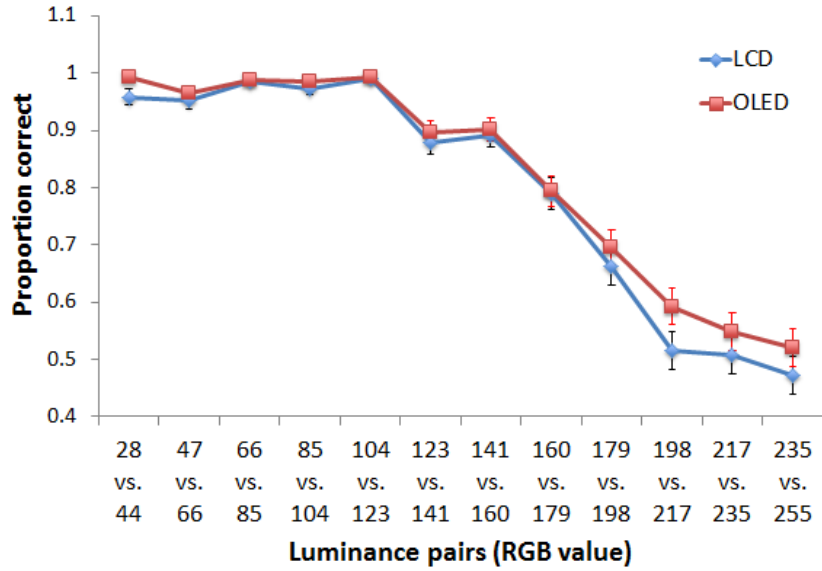
Luminance Comparison

Figure 2 show the accuracy of discerning which of the two luminance targets was brighter. Figure 2A shows the results plotted against the gray levels and corresponding luminance levels, whereas Figure 2B shows the contrast ratio derived from the actual differences in luminance levels divided by the luminance of the dimmer target. The actual luminance levels were measured with these circles presented and measured individually.

Figure 2A shows that with lower gray levels (123 vs. 141 or lower), the ability to discern the difference reached the ceiling and was near perfection. The accuracy decreased gradually until it reached the chance level at gray levels 198 vs. 217. Beyond which little difference in accuracy was seen and it was mostly around 50%. Interestingly, both TVs showed a similar decrease, although the accuracy with the OLED TV was significantly better than the LCD TV with the largest gray levels.

The decrease in discrimination accuracy with larger gray levels seems surprising, as the actual luminance differences between were larger in the latter pairs of gray levels. Figure 2B revealed that the better performance with OLED TV was largely explained by the larger contrast ratios. The larger luminance difference in the pairs of larger gray levels in LCD and OLED actually resulted in smaller contrast ratios and poorer accuracy because of the high luminance level.

A.



B.

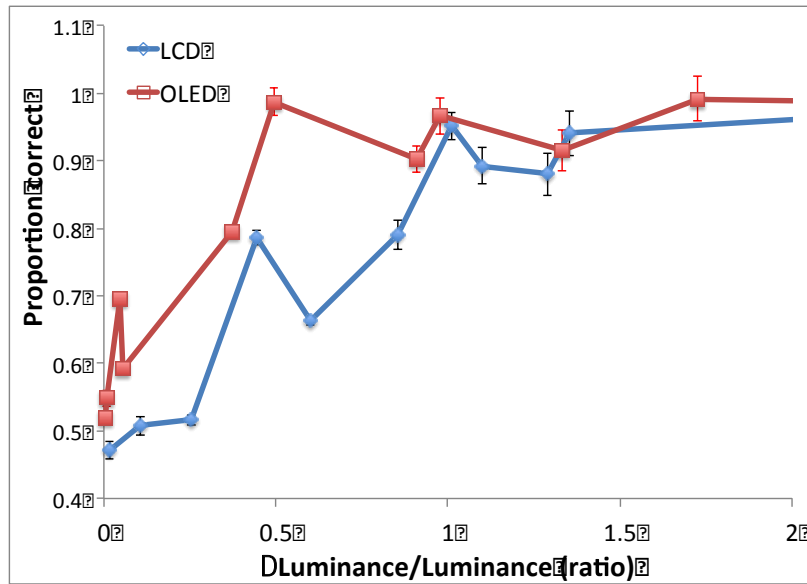


Figure 2. Response accuracy in luminance comparison task. A) Response accuracy relative to the adjacent pairs of gray levels. Each data point in the figure is based on 1680 samples; error bars indicate standard errors. B) Response accuracy relative to the ratio of luminance difference against the lower luminance level.

To assess how the viewers utilized luminance and contrast signals to discern brightness, the receiver operation characteristic (ROC) curve was constructed based on the choices (which circle is brighter) relative to absolute luminance difference and contrast ratio (absolute luminance difference between two circles divided by the lower luminance of the two circles) of the two luminance levels. A larger AUC value (shown in the panels) indicates the better ability to choose the brighter target. Figure 3 show the ROC curves for the choices based on absolute luminance difference. The OLED screen (AUC = $.685 \pm .008$) provided much better sensitivity (correct hit) and specificity (1 - false alarm) than the LCD screen (AUC = $.550 \pm .010$, $p = .0004$).

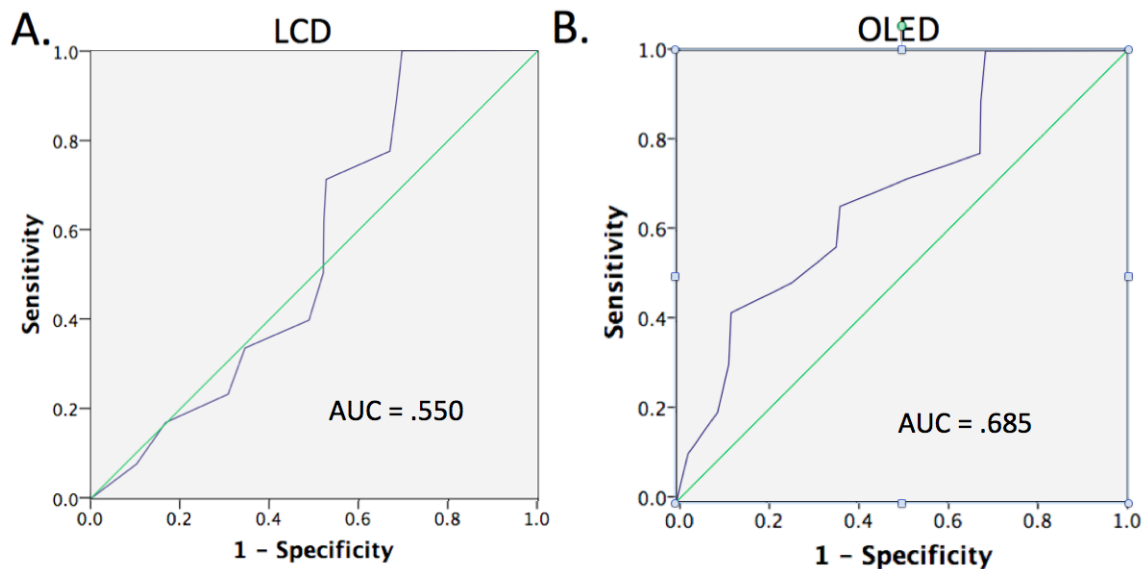


Figure 3. Receiver operating characteristics (ROC) curve for brightness choice based on absolute luminance difference with LCD (left panel) and OLED (right panel). The diagonal line indicates random guessing.

Figure 4 shows the area under the curve (AUC) based on contrast ratio. The OLED screen ($AUC = .783 \pm .006$) provided only slightly higher sensitivity (correct hit) and specificity (false alarm) to the LCD screen ($AUC = .763 \pm .006$, $p = .142$). Therefore, when the actual luminance difference was used to predict the accuracy of choices, OLED screen was much better in allowing the participants to make the correct choices. Conversely, participants were able to achieve the same level of accuracy in luminance comparison with both LCD and OLED screens when the determining stimulus is the contrast ratio.

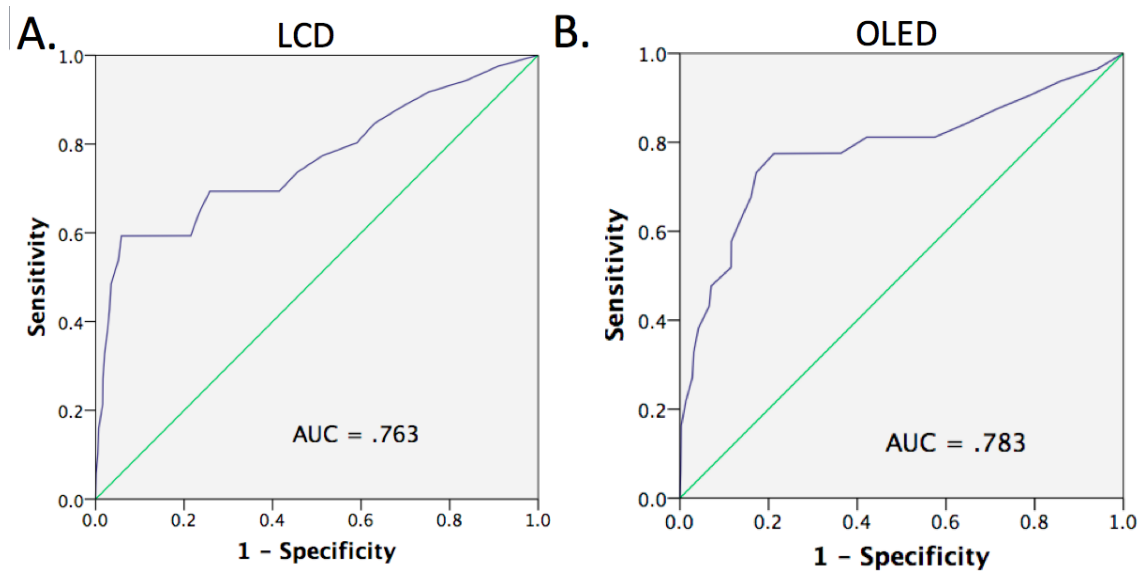


Figure 4. Receiver operating characteristics (ROC) curve for brightness choice based on contrast ratio with LCD (left panel) and OLED (right panel).

Because the upper luminance range of the displays is of particular interest to the study, 10 more participants were recruited to discriminate between gray levels 179, 198, 217, 235 and 255 in pairwise manner. Table 2 shows that Gray level above 179 can be differentiated from 179 itself; however, gray level 198 cannot be differentiated from

217, 235 and 255. These support gray level 179 (695 nits) as the maximal luminance with which image brightness can be reliably differentiated.

Table 1. Percentages of accuracy and their 95% confidence intervals in identifying the brighter target in the luminance comparison task with the LCD TV. Asterisks (*) indicate a percentage is significantly higher than the 50% level (change guessing).

Gray Level	179	198	217	235
179				
198	0.655±.112*			
217	0.685±.109*	0.615±.115		
235	0.650±.112*	0.60±.115	0.485±.118	
255	0.675±.110*	0.59±.116	0.56±.117	0.49±.118

*, p < .05

Based on the above sets of results, a regression model was conducted to determine the threshold contrast ratio for the response accuracy of 75%. Figure 5 shows the relationship between contrast ratio and discrimination accuracy based on the data from Figure 2B (with contrast ratio greater than 1 excluded to avoid the ceiling effect). The regression model accounts for 71.1% of variance (R^2) and have a contrast threshold of .59 for the .75 accuracy threshold. The 75% discrimination accuracy is the typical psychophysical threshold for detecting just noticeable difference (JNF).

Based on the above model, the effective range of maximum luminance can be estimated: For the OLED screen, the actual maximum luminance 647 cd/m² cannot be readily differentiated from 404 to 1029 cd/m², namely any luminance below 1029 and

larger than 407 cd/m² would not be reliably differentiated as different from 647 cd/m². Conversely, for the LCD screen, the actual maximum luminance 1568 cd/m² cannot be differentiated from 986 to 2493 cd/m². The slight overlap between these two ranges suggests the maximum luminance of the OLED and LCD screens can be reliably discriminated at close to 75% of accuracy.

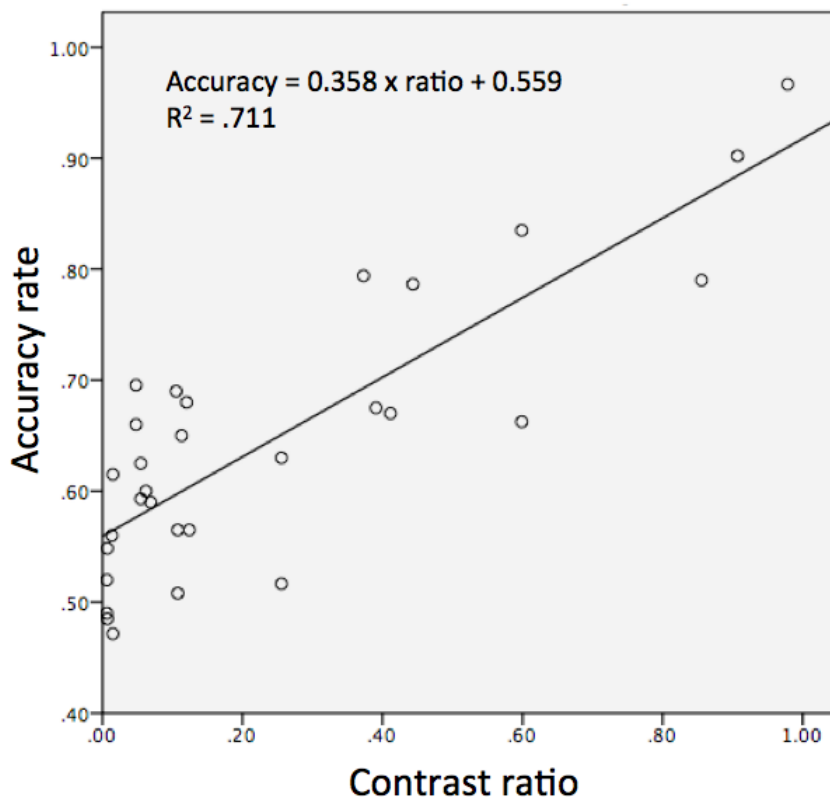


Figure 5. Scatter plot and regression outcomes for contrast ratio and brightness discrimination. The linear regression model was shown in the figure. Data points include outcomes from trials obtained from both LCD and OLED displays.

To confirm this, participants were asked to perform an additional task where they viewed images with the same gray level on the two screens but different luminance levels. They were asked to indicate which one was brighter. Their probability of selecting

the correct one was also estimated based on the regression model reported above.

Figure 6 shows the empirically measured probability and its 95% confidence intervals and the estimated probabilities. It appears that the model underestimated the tendency of selecting LCD as brighter in the low luminance range and overestimated in the high luminance range.

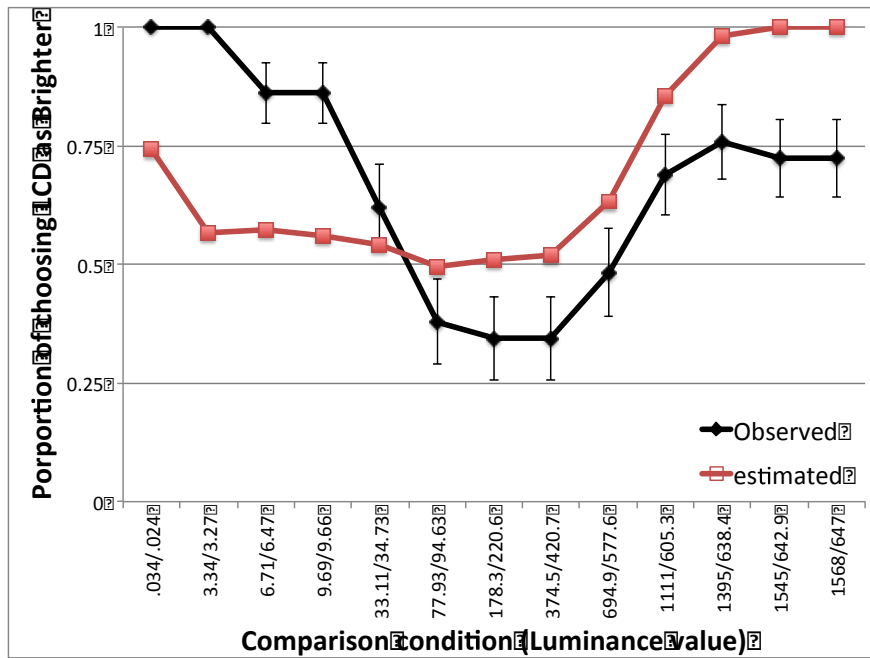


Figure 6. Proportion of selecting LCD as brighter relative to the luminance values of images displayed on LCD and OLED screens. The observed data (black) was measured from side-by-side comparison of images with the same gray level but on separate screens. The estimated values (red) were based on the regression model.

3.2 Orientation discrimination task

The orientation discrimination task investigated the relationship between the luminance of background mask and the accuracy of discerning grating orientation, and its effect on visual discomfort. To address these questions, in the orientation

discrimination task the same luminance circle was presented immediately before the presentation of grating targets. This allowed the impact of screen luminance on visual processing to be assessed both physiologically by inspecting the visually-evoked potentials and behaviorally by measuring the ability to perceive the orientation of grating targets.

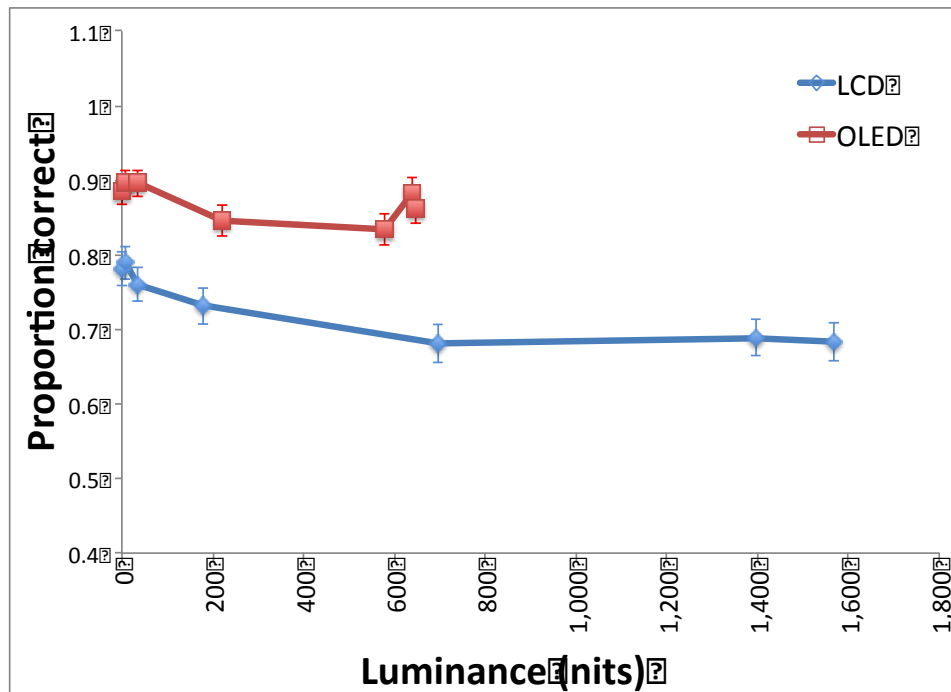


Figure 7. Proportion of correct responses in discerning the orientation of grating target. Here the X axis shows the actual luminance of the homogenous background circle. Error bars indicate standard errors.

Figure 7 shows the seven levels of luminance had an effect on response accuracy starting at 178 cd/m² for LCD and 221 cd/m² for OLED, and the decrease bottomed out at 578 for OLED and 695 for LCD. Notably, the OLED screen maintained constantly

higher accuracy over the LCD screen, even when its actual luminance was slightly higher than LCD with gray levels 141 and 179.

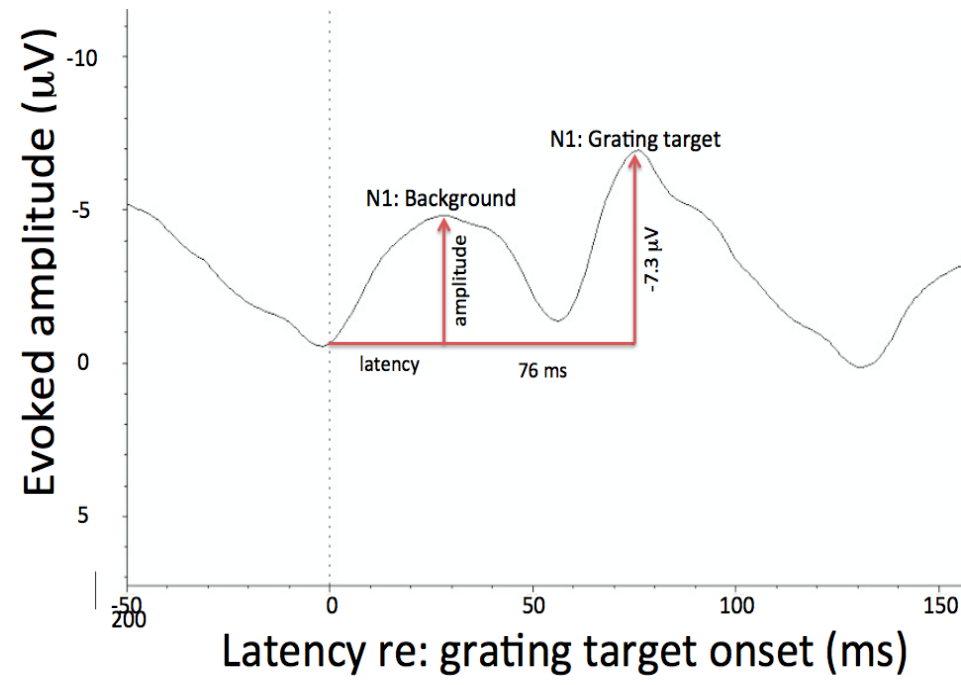


Figure 8. Example of visually-evoked potential recorded from the Oz (central occipital lobe) site obtained from a single participant and averaged over 20 trials. Negative amplitude was plotted as upward in the Y axis and the timeline on the X axis was relative to the onset of grating target.

Figure 8 shows an example of averaged N1 amplitude measured with VEP from a block of trials with 695 cd/m^2 luminance on the LCD screen. Note that the first negative peaked after target onset was at 28 ms, clearly suggesting it was caused by the bright luminance background. In contrast, the second negative peak appeared at 76 ms after target onset, which was associated with the grating target itself. A higher N1 amplitude reflects greater cortical stimulation and predicts a higher stimulus encoding but also

higher level of visual discomfort. Armed with this knowledge, it is easier to see in Figure 9A that the N1 amplitude remained at about the same level until it started to increase at gray 179 (649 cd/m²) for LCD screen; the OLED did not induce any significant increase (578 cd/m²). Consequently, in Figure 9B the peak amplitude associated with the grating target was significantly reduced when the luminance was above OLED 578/LCD 695, indicating the target was more poorly encoded. These are consistent with the behavioral data reported in Figure 7.

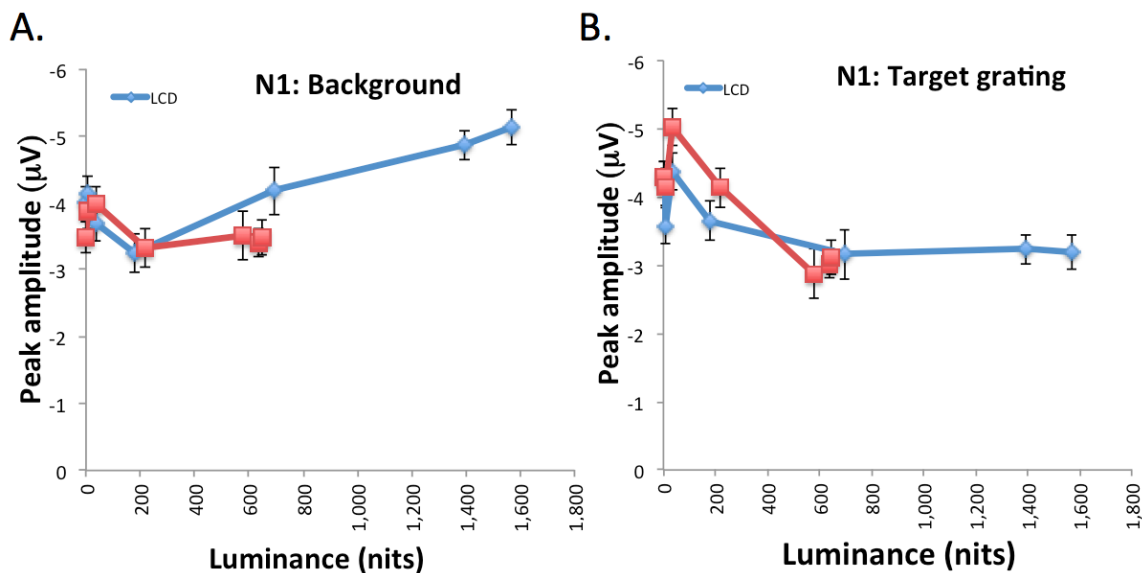


Figure 9. Peak N1 amplitude recorded during the orientation discrimination task. A) Peak amplitude of N1 elicited by homogenous luminance circle. Error bars indicate standard errors. B) Peak N1 amplitude elicited by grating targets.

Figures 10 revealed the level of visual discomfort associated with LCD and OLED screens after each block of 20 orientation discrimination trials. Note that the discomfort level increased as the luminance level was higher. OLED reached its asymptote at 578 cd/m² whereas the LCD continued to increase until 1568 cd/m². In addition, the

discomfort level was higher for LCD when its luminance level was higher than that for OLED.

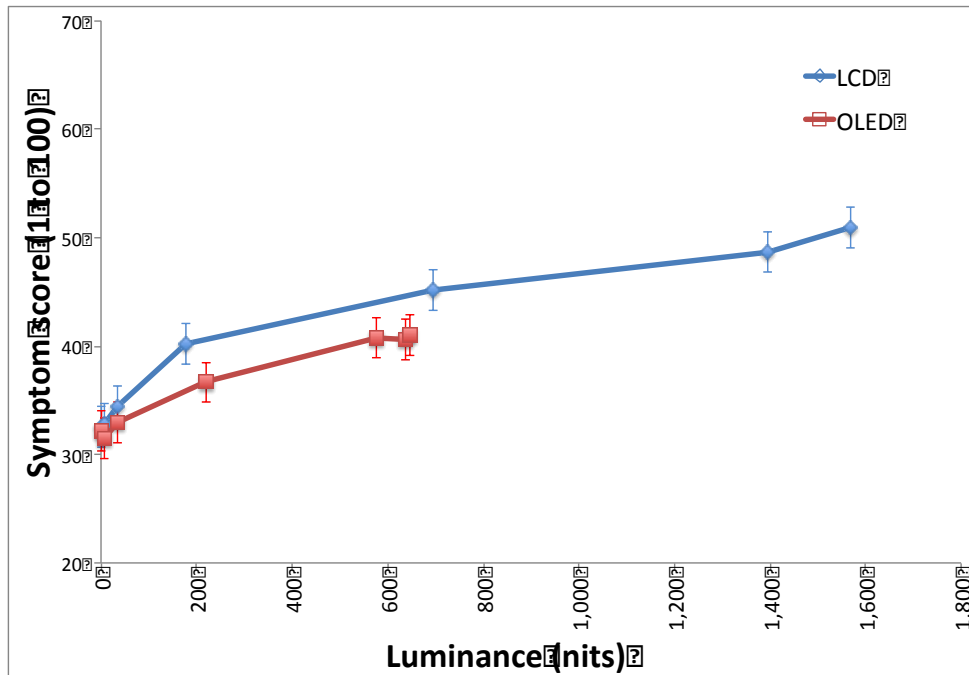


Figure 10. Perceived visual discomfort obtained with an analog scale (1 - 100) after a block of orientation discrimination trials. The X axis indicates luminance level; error bars indicate standard errors.

To determine at which level of luminance was the visual discomfort significantly elevated, the discomfort score with gray level 28 for each participant (below the gray level of 65 for the darker lines in the grating stimulus) was treated as the baseline and any increase in symptom score larger than the .5 standard error of symptom score for the baseline was considered as significantly elevated. Table 2 shows the percentages of participants having an increase of symptom level larger than .5 SD of symptom with gray level 28 ($SE_{LCD} = 20.21$, $SE_{OLED} = 22.14$). Z and p values indicate the significance of

percentage difference between LCD and OLED. Asterisks (*, **, ***) indicate the significance of difference in percentage between the corresponding gray level and Gray level 28. These results indicated that Gray level 179 for LCD (695 cd/m²) and 217 for OLED (605 cd/m²) are the threshold luminance with which a significant proportion of subjects (43%) had an increase in their visual discomfort, compared to the baseline with gray level 28.

Table 2. Proportion of participants with elevated discomfort at tested gray levels compared to the baseline (gray level 28). Asterisks indicate significantly increases compared to the discomfort level in gray level 28. Z and p values indicate significant differences between LCD and OLED in the proportion of participants with increased discomfort.

Gray Level	Luminance Level (nits)		% of Subject with Symptom Increased by 25%		Z	P
	LCD	OLED	LCD	OLED		
66	6.71	6.41	0.19	0.095	1.1	0.1312
104	34.73	34.7	0.147	0.088	0.8	0.45
141	178.3	220.6	0.29	0.14	1.7	0.0434
179	694.9	577.6	0.43*	0.22	2.1	0.0177
217	1395	638.4	0.57**	0.31*	2.5	0.007
255	1568	647	0.62***	0.41**	2	0.0244

*, p < 0.05; **, p < 0.01; ***, p < 0.001

Chromatic Targets for Orientation Discrimination

Figure 11 shows results obtained with chromatic stimuli. The results clearly how OLED led to better visual discrimination than LCD overall, but showed no clear change in response accuracy relative to luminance level. This is not surprising, as the luminance

circle did not washout the neural responses of the opposing color and thus would not affect the identification of corresponding lines in the grating (e.g., red circle not washing out neurons for green perception).

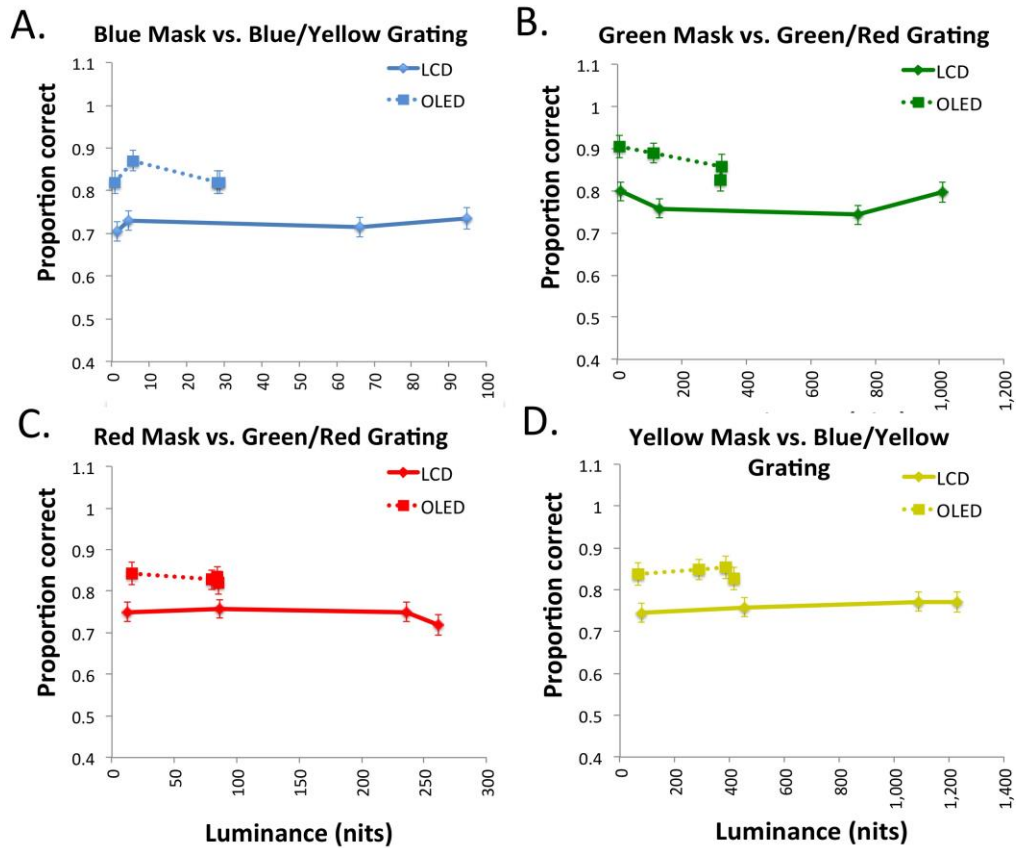


Figure 11. Discrimination accuracy for chromatic grating targets relative to the luminance level.

Movie Viewing and Symptom

The viewing symptom survey was measured immediately before and after 30 mins of viewing. After 30 Mins of viewing, LCD induced a greater level of averaged viewing symptoms (39.7 ± 1.24 out of 100) compared to OLED screens (36.4 ± 1.17 , $p = .034$). LCD induced higher symptoms over OLED in memory, image jumping, double

vision, dizziness, tired eyes and fatigue, which contributed to the higher averaged symptoms for LCD.

Discussions

The present study aimed to understand human ability to differentiate screen luminance and to investigate the threshold of screen luminance for visual discrimination and viewing comfort. Results show **contrast ratio is better in predicting brightness discrimination and** resultant regression model suggests 59% contrast is needed to reach 75% accuracy. Based on the model, the maximal OLED luminance (**647 cd/m²**) was **perceived as bright as 1035 cd/m² on LCD screen. Additional results revealed that the threshold luminance for visual performance and discomfort is 695 cd/m².** The VEP signals associated with the luminance level increased along with viewing discomfort and the signals associated with the grating target decreased along the reduced accuracy of orientation discrimination. The **OLED is visually more comfortable and affords better visual performance than LCD when the screen luminance is high due to its high contrast.** These findings suggest higher contrast ratio rather than greater luminance difference is important for brightness discrimination. To reduce visual discomfort while achieving better visual performance in dynamic images, better contrast ratio and black level are more important than greater screen luminance. The following discussions are attempted to inform the decisions on selecting the correct luminance range in HDR displays.

HDR Displays and Luminance Range

The invention of HDR algorithms has been intended to provide similar experiences of the luminance range afforded by the natural environment. However, actual research on human perception of the HDR displays has been lacking. The present study examined this issue by first empirically measuring the actual luminance generated by state of art LCD and OLED TVs. Figure 1 clearly demonstrated distinct range of luminance: whereas the two TVs were quite similar in luminance level for the lower gray levels, the LCD TV generated much higher luminance with higher gray levels, up to 1568 cd/m². However, when we consider the ability to discriminate brightness difference, absolute luminance difference was not a good predictor of behavioral choices; rather, the contrast ratio was a better predictor for both LCD and OLED screens. Present results clear showed that both types of display are comparable in differentiating luminance levels if the contrast ratio provided by them were the same.

The regression model based on the present outcomes was adequate in illustrating the relationship between contrast ratio and brightness discrimination in human perception. However, it was poorer in predicting the accuracy at low and high ends of the contrast ratios. As shown in Figure 6, the underestimation of selecting LCD as brighter in the lower range of contrast ratio can be explained by the light leakage of LCD screen, which generates higher luminance than intended and could shift the choice toward the image displayed on the LCD screen.

The use of HDR algorithm in image rendering depends on the luminance capacity of specific displays. The two TVs tested in the present study show that the higher

luminance range is not as effective in affording differential brightness perception. This is likely due to the neurophysiological ceiling of human visual system in responding light stimulation. It is also clear that the display technology affects the brightness discrimination at the lower and higher end of gray level due to light leakage and achieved black level. Therefore, when developing HDR algorithms, the actual level of contrast ratio at both ends of HDR could be more important than actual luminance level. It might be useful to adjust the HDR algorithm based on the properties of individual displays.

Threshold Luminance for Visual Performance

The second critical question the study aimed to address is the threshold luminance for human perception, in the context of dynamic image viewing. The study postulated that the swift change in screen luminance from very bright to very dark images might significantly impact visual performance and comfort. The present results suggest, again as predicted by log law of human luminance perception, the increase of screen luminance had diminished effect of luminance differentiation. Results from figure 2 suggest the luminance level of 695 cd/m^2 is the perceptual limit, as defined by the 75% accuracy threshold, beyond which added luminance did not reliably increase the ability to differentiate luminance levels. For instance, to further increase the range of perceived brightness, based on our regression model the OLED screen need to increase from 647 to 1035 cd/m^2 , and the LCD screen needs to increase from 1568 to 2493 cd/m^2 . As such, it will be extremely inefficient to enhance brightness perception by

further elevating screen luminance. Rather, the reduction in light leakage and the achievement of low black level might be more beneficial.

In screen viewing, the foveal vision often shifts from a bright area to a dim one, or vice versa. Therefore, the processing of high luminance image might have an impact on the processing of subsequent images. Results from orientation discrimination task suggest this threshold is also important for visual performance. The ability to see the grating targets began to decrease at 178 (LCD) to 221 cd/m^2 (OLED) and reached its bottom at 695 (LCD) and 578 cd/m^2 (OLED). Therefore, to maintain good visual performance on the dimmer aspect of dynamic image, the luminance should be kept at an as lower level as the HDR algorithm can permit.

Threshold luminance for Visual Comfort

Another important question for screen luminance is viewing comfort. Individuals have variable threshold luminance for viewing comfort. Strong light immediately incurs debilitating symptoms for most people, but even moderate light stimulation such as TV viewing can induce discomfort for some viewers. Recorded VEP signals in the present study suggest the visual activity continued to increase up to 1568 cd/m^2 with LCD even as the subjective luminance difference was not reliably discerned. The OLED screen also led to increased subjective discomfort and the increase was parallel to but lower than the LCD screen. Correspondingly, the VEP signal in response to the luminance level also stabilized at the same luminance levels. These findings demonstrated a clear relationship between brightness perception and VEP activities.

Our findings in Figure 8 suggest the initial increases of visual discomfort were observed at a relatively low luminance level, 178 cd/m² for LCD and 221 cd/m² for OLED. The discomfort level continued to increase as the luminance level was raised. The proportion of participants having elevated discomfort reached statistical significance at 697 cd/m² for LCD and 605 cd/m² for OLED. Correspondingly, the VEP signals were elevated along with the increases in screen luminance, despite of the limited ability to further discern brightness at the higher range of luminance. The light-induced discomfort might be modulated by the actual luminance level of light, not the subjective perception of brightness.

Therefore, there does not exist a well-defined luminance threshold for visual discomfort; individual viewers might react differently to luminance stimulation. However, there is a definite relationship between luminance level and neural stimulation that causes visual discomfort. Our data suggest the luminance level of 605 to 695 cd/m² is critical in causing a larger proportion of individuals to perceive elevated discomfort. This is consistent with previous recommendations (Society of illumination Engineers, 1974). These findings suggest that despite of individual differences, the luminance level should be not further elevated when their visual performance is not further facilitated by higher luminance level. The 695 cd/m² threshold of luminance might be the preferred threshold of luminance for both visual performance and comfort.

Our results suggest chromatic luminance only selectively washouts the corresponding neural pathways, leaving stimuli with the opposing color unaffected. As

a result, the increasing luminance level did not lead to poorer orientation discrimination. However, the OLED led to consistently higher accuracy than LCD, supporting the importance of image contrast in visual discrimination.

Conclusion

The present studies investigated the threshold luminance for visual performance and comfort with HDR displays. We asked whether the typical viewers could discern the full range of luminance provided by the HDR displays. Our findings suggest that contrast ratio is the main determining factor rather than luminance difference. As a result, a larger portion of LCD luminance cannot be appreciated by the viewers compared to OLED luminance.

Our findings also suggest that higher luminance caused the visual system to subsequently lose its ability to encode visual information and to increase the perceived discomfort by over-activating the visual cortex. This effect is at least supported by the neurophysiological signals recorded from the visual cortex, where the activity associated with the luminance circle was positively correlated to visual discomfort, and negatively correlated to visual identification. As a result, participants were impeded in discerning an otherwise easily identified grating target without the prior light stimulation. These findings suggest overly high luminance impede the viewing of dynamic scenes where luminance change is swift and large.

The present studies suggest that the range of luminance useful to HDR rendering in human viewers is limited and the other quality of display technology such as black

level and contrast ratio are even more important in determining visual performance. Visual discomfort also can be elevated for a larger portion of viewers when the luminance reaches a threshold around 605 to 695 cd/m². Future studies should use more natural and realistic images to test the visual performance and comfort under sustained viewing conditions.

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